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TITLE: NEUTRON-ANTINEUTRON CONVERSION EXPERIMENTS

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NEUTRON-ANTINEUTRON CONVERSION EXPERIMENTS*

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1. Introduction

A great deal of attention has been given in this Workshop to proton decay experiments. These experiments look for a violation of baryon number $\Delta B = 1$, as predicted by Grand Unified Theories. There are many experiments searching for proton decay in deep mines and tunnels, all over the world. Some are in progress, others expect to start operating soon, and although clear positive evidence is still lacking second generation experiments are being actively proposed. All are being followed with great interest for the evidence they should provide about the validity and the nature of these theories.

There is another class of experiments which bears on the same question in a different way. These also search for a violation of baryon number, but with $\Delta B = 2$. With $\Delta B = 2$ the spontaneous conversion of a neutron to an antineutron, $n \to \bar{n}$, becomes possible. In a number of unified theories the predicted rate of $n \to \bar{n}$ conversion is within the range of experimental possibility.

To my knowledge, the first reference to the $n \to \bar{n}$ process appears in a paper by M. Gell Mann and A. Pais,[1] entitled, "Behavior of neutral particles under charge conjugation". The process is allowed under charge conjugation, but requires $\Delta B = 2$. In 1955, baryon number conservation was considered to be an inviolable property of nature so the further implications of the process were not pursued. However, the paper set the groundwork for another process involving charge conjugation, namely the process $K^0 \rightleftarrows \bar{K}^0$ which can proceed under a violation of strangeness conservation, $\Delta S = 2$, for which there were no established prejudice. The subject was revived again in 1970 by V. A. Kuz'min,[2] in a paper under the title, "CP non-invariance and the baryon asymmetry of the universe". In this paper Kuz'min actually estimated the mixing time and showed that a measurement was feasible. However, no attempt to carry out such an experiment was made. The experimentalists got into the act after S. L. Glashow,[3] high priest of Grand Unification, launched his campaign to emphasize the importance and the challenges of experiments that would provide a realistic basis for these ideas. For the $n \to \bar{n}$ process he proposed an extension of SU(5) with a 6-fermion coupling that would allow the annihilation of 6 quarks, or alternatively, the conversion of 3 quarks into 3 anti-quarks. The diagram for this process is shown in Figure 1.

Glashow estimated an upper bound for the interaction strength of this coupling from the lower bound on nuclear stability.[4,5] Thus, with $\Gamma = \hbar/10^{30}$y and m somewhat larger than the nucleon mass we have,

$$\delta m \approx \sqrt{\Gamma m} \approx 10^{-21} \text{ eV} \ .$$

Using the relation $\delta m \approx m^6/M^5$, appropriate to a 6-fermion coupling, the unification mass turns out to be $M \approx 10^6$ GeV. This is much smaller than the value 10^{15} GeV which characterizes simple SU(5). Because of the M^{-5} behavior of the interaction strength in the 6-fermion coupling, it is clear that if SU(5) turns out to be the correct theory the [illegible] for observing $n \to \bar{n}$ will be vanishingly small. However, there are other theories of the Pati-Salam type in which [illegible] mass emerges naturally. Such intermediate values for the [illegible] mass are also characteristic of theories [illegible]. Recently, [illegible] and Marshak[6] have described a [illegible] in which the $n \to \bar{n}$ process arises in a "natural" way. It appears [illegible]

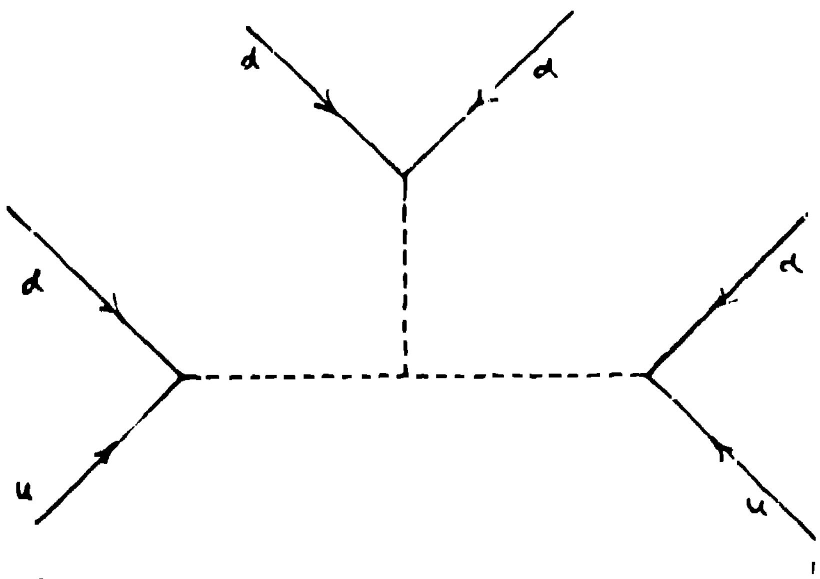

Figure 1 Annihilation of 6 quarks according to Glashow.[3]

Table 1 Theories predicting proton decay or n-n̄ conversion

Proton Decay	$n \to \bar{n}$	Theory	
yes	no	GUT	SU(5) type grand unified theory
yes	yes	EUT	extended unified theory
no	yes	PUT	partial unified theory
no	no	???	unified theory unknown

version is complementary to proton decay in demonstrating which of many possible unification theories nature follows. The above chart, due to Chang,[2] displays how the outcome of proton decay or $n \to \bar{n}$ conversion experiments can help decide which of the theories might have some validity.

2. Neutron-Antineutron Conversion

The physics involved in the process $n \to \bar{n}$ with $\Delta B = 2$ is anal[illegible] to the process $K^0 \to \bar{K}^0$ with $\Delta S = 2$. The neutron and antineutron [illegible] treated as members of a two component system. The system which [illegible] start out at $t = 0$ as a pure neutron amplitude will, if unperturbed, as time goes on, build up an appreciable antineutron amplitude. The time available for the conversion is limited by neutron beta decay, [illegible] mean life is $\sim 10^3$ seconds.

In the unperturbed case, e.g., in the absence of [illegible], the time behavior of the system is determined by the [illegible] operator,

$$\begin{pmatrix} E_0 & \delta m \\ \delta m & E_0 \end{pmatrix}$$

where E_0 is the energy of the free neutron which can be taken [illegible] rest mass, the same for n as for $\bar{n}$; and δm is the perturbation [illegible] through which the transition $n \to \bar{n}$ proceeds. Glashow's estimate, $\delta m < 10^{-21}$ eV, emphasizes how small the interaction is.

In practice, the energies of n and $\bar{n}$ are not exactly the same because of the presence of the earth's magnetic field. We write [illegible] and recognize that the magnetic moment, while the same in magnitude, has opposite signs for n and $\bar{n}$. Thus, the Hamiltonian operator is written

$$\begin{pmatrix} E_o + \Delta E & \delta m \\ \delta m & E_o - \Delta E \end{pmatrix} .$$

If an $n - \bar{n}$ mixing exists, neutrons and antineutrons are no longer eigenstates but can be expressed as a mixture of new eigenstates n_1 and n_2,

$$n = n_1 \cos\theta + n_2 \sin\theta ,$$
$$\bar{n} = -n_1 \sin\theta + n_2 \cos\theta ,$$

with $\tan 2\theta = \delta m/\Delta E$.

In a neutron beam the new states change phase with time according to

$$n_1(t) = n_1(0) \exp(-iE_1 t/\hbar) ,$$
$$n_2(t) = n_2(0) \exp(-iE_2 t/\hbar) .$$

E_1 and E_2 are the eigenvalues of energy obtained by diagonalizing the matrix,

$$E_1 = E_o + (\delta m^2 + \Delta E^2)^{1/2} ,$$
$$E_2 = E_o - (\delta m^2 + \Delta E^2)^{1/2} .$$

Thus,

$$n(t) = n_1(0) \exp(-iE_1 t/\hbar) \cos\theta + n_2(0) \exp(-iE_2 t/\hbar) \sin\theta .$$

The probability of an $n \to \bar{n}$ conversion after a time t is obtained by calculating the overlap of $\bar{n}$ with n(t) and squaring

$$P_{\bar{n}}(t) = |\langle \bar{n} | n(t) \rangle|^2 ,$$

with the result

$$P_{\bar{n}}(t) = \frac{\delta m^2}{\delta m^2 + \Delta E^2} \sin^2 [(\delta m^2 + \Delta E^2)^{1/2} t/\hbar] e^{-\lambda t} ,$$

where the extra factor $e^{-\lambda t}$ has been added to take into account the beta decay of the neutron.

Table 2 Number of events in a plausible experiment

$\tau = 10^{6}$ sec

$\delta m = 7 \times 10^{-22}$ eV

$\phi = 10^{12}$ n/s

$T = 10^{7}$ sec

ℓ = 50 meters, drift length

v = 2500 m/s neutron velocity

$t = 2 \times 10^{-2}$ sec, drift time

$\varepsilon = 0.5$

$\tau' = \hbar/(\delta m^{2} + \Delta E^{2})^{1/2}$

H gauss	ΔE eV	τ' s	
0.0	0	10^{6}	2×10^{3}
0.5	3×10^{-12}	2×10^{-4}	1×10^{-1}
10^{-3}	6×10^{-15}	10^{-1}	2×10^{3}

We refer to $\tau = \hbar/\delta m$ as the mixing time. For $\delta m = 10^{-21}$ eV, $\tau = 7 \times 10^{5}$ seconds. We refer to $\tau' = \hbar/(\delta m^{2} + \Delta E^{2})^{1/2}$ as the oscillation time. For $\Delta E = \mu B$ with $B = 0.5$ gauss, $\Delta E = 3 \times 10^{-12}$ eV and $\tau' = 2 \times 10^{-4}$ seconds.

The number of $n \to \bar{n}$ conversions detected in a time of observation T is,

$$N = P_{\bar{n}}(t)\,\phi T \varepsilon \quad ,$$

where ϕ is the flux, the number of neutrons/s in the beam, and ε is the detection efficiency. Plausible values give the numbers listed in Table 2.

The importance of magnetic field shielding in the experiment is shown in Figure 2. The relative conversion probability has been calculated for a thermal neutron beam having a Maxwellian distribution of velocities corresponding to a temperature of 400°K and a drift length of 10 meters. For this plot $\int B\,dl$ is an invariant so the values of B have to be divided by 5 if the drift length is 50 meters. It can be seen that if the loss in conversion is to be kept below 10[illegible], the magnetic field intensity must be kept below 1.2×10^{-3} gauss. This requires a rather elaborate mu-metal shield together with current

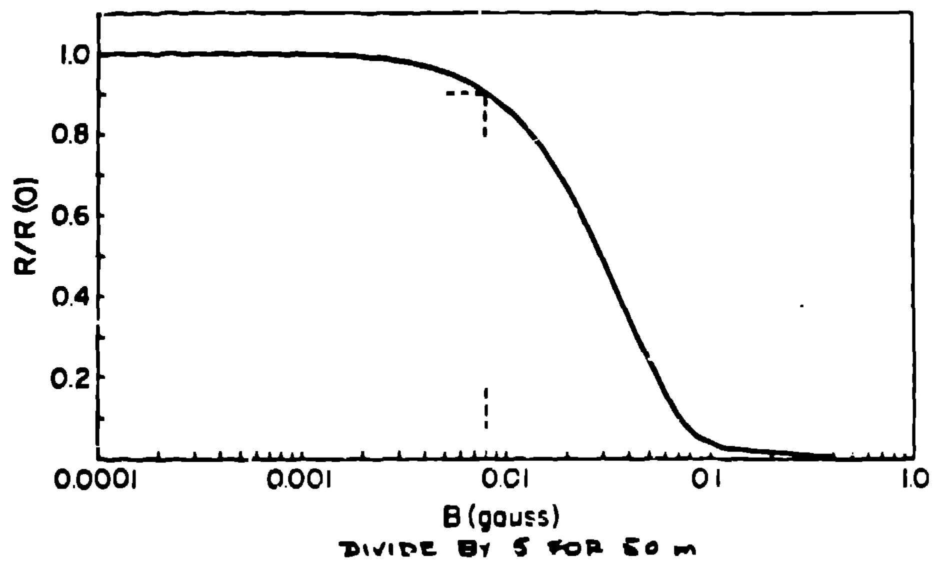

Figure 2 Effect of magnetic field on $n - \bar{n}$ conversion. The curve is calculated for a 10 meter drift length and a Maxwellian distribution of velocities at T = 400°K. Values along the abscissa should be divided by 5 for a 50 meter drift length.

carrying coils to buck out residual fields. An advantage of this sensitivity to magnetic field is that the effect can be turned off and a reliable background rate established by operating with a field above 0.1 gauss.

3. Experimental Limit

The $n \to \bar{n}$ process can occur spontaneously in nuclear matter and give rise to a striking signature, the release of 2 GeV in energy when the $\bar{n}$ annihilates with another nucleon in the same nucleus. There is an emission of 4-5 pions on average, some of which may be π^+ which escape absorption and decay to μ^+. Such $\pi^+ \to \mu^+$ decays have been looked for by Learned et al.[4] and more recently by Cherry et al.,[5] in deep mine experiments. These experiments have been used to set a limit of $>10^{30}$ years for proton decay. To the extent that the branching ratio for the production of π^+ in proton decay is not very different from that in $\bar{n}$ annihilation, we can take the same lifetime to apply to either type of nucleon instability.

We can make a rough estimate of this lifetime by calculating the transition rate using Fermi's Golden Rule,

$$\Gamma = \frac{2\pi}{\hbar} |H|^2 \frac{dN}{dE} \quad ,$$

where the transition matrix element $H = \delta m$ x an overlap integral, and dN/dE is the number of final states per unit energy interval. Using plausible values, a level spacing, $(dN/dE)^{-1} \approx 1$ GeV, a mixing time of 10^6 seconds, and taking the overlap between two nucleons in a nucleus to be of the order of 10^{-2} (Mohapatra and Marshak[7] estimate), we obtain $\Gamma^{-1} = 7 \times 10^{29}$ years. Thus, an experiment on neutron-antineutron conversion that sets a mixing time $>10^6$ seconds will establish a new limit for nucleon stability for this type of process.

Various estimates of the mixing time based on the experimental limit for nucleon stability have appeared in the literature. Although the formulas obtained may be accurate enough, the results differ because the parameters are not so well known. These estimates are listed in Table 3.

It appears that experiments with a sensitivity $\tau = 10^7$ would be quite important. Because of the quadratic dependence $\Gamma^{-1} \propto \tau^2$, a sensitivity of 10^8-10^9 s would allow the experiment to explore the stability of matter in the range 10^{32}-10^{34} years, namely in the region of the most ambitious projects to search for proton decay.

Table 3 Estimates of mixing time

Ref.	Year	Author	Limits Γ^{-1}	Limits τ_{nn} (s)
2	1970	V.A. Kuz'min	-	10^4/[illegible]
3	1979	S.L. Glashow	-	10^5-10^6
7	1980	R.N. Mohapatra and R.E. Marshak	10^{30} y	10^5
8	1980	M.V. Kazarnovskii et al.	10^{30} y	2×10^7
9	1981	K.G. Chetyrkin et al.	3×10^{30} y	3×10^7
10	1980	P.G.H. Sandars	10^{30} y	1.8×10^7
11	1981	Riazzudin	10^{30} y	3×10^6
12	1980	L.N. Chang and N.P. Chang	10^{30} y	10^7
13	1980	R. Cowsik and S. Nussinov	10^{31} y	5×10^7

4. The n-$\bar{n}$ Conversion Experiment

To observe the conversion n-$\bar{n}$ we arrange to have a large number of neutrons moving as slowly as possible within a long evacuated drift space carefully shielded from magnetic fields. The interaction of $\bar{n}$ with the target produces a spectacular signature. The annihilation reaction $\bar{n}$n or $\bar{n}$p occurs in the nucleus with a high cross-section and results in the emission of 4-5 pions on average, and the release of 2 GeV in energy. However, to realize the full sensitivity needed in such an experiment, the utmost care must be taken in the design of the detector so that it will distinguish, with a high degree of certainty, annihilation events from the cosmic ray background. The difficulty comes from the fact that if 1 event is found after 1 year of running, we want to be sure it is an annihilation event and not caused by one of the 10^{11} cosmic rays that have traversed the detector during this time. Moreover, the detector must function almost perfectly in the presence of a large background of the capture gamma rays that invariably accompany slow neutrons.

5. Annihilation Events

Although the annihilation events are quite striking, involving the emission of 4-5 pions on average, their energy is in the range of several MeV, appreciably lower than the multi-GeV particles that high energy experimentalists have become accustomed to. The rest mass of the charged pions accounts for a substantial fraction of the 2 GeV available, and since the probability of a nuclear interaction is high, much of the energy goes into nuclear excitation and disintegration. A good detector will make this energy visible. Multiple scattering is more serious with these low energy particles, making it more difficult to reconstruct the vertex.

The characteristics of the annihilation events are known in considerable detail from studies that have been made of $\bar{p}$p annihilations at rest. The branching ratios for the different modes of annihilation are given in Table 4.[14] The difference in the case of $\bar{n}$n should be minor because the same isotopic spin is involved in the initial state. In the case of $\bar{n}$p annihilation a different charge and isotopic state is involved and some difference in the charge composition of the pions emitted can be expected.[15] The mean multiplicities and energies of

Table 4 Contribution of pionic states to $\bar{p}p$ annihilations at rest*

Final state	Resonant intermediate state	Percentage of all annihilations CERN	Columbia
All neutral particles		$4.1^{+0.2}_{-0.6}$	3.2 ±0.5
$\pi^+\pi^-$		0.37±0.03	0.32±0.03
$\pi^+\pi^-\pi^0$		6.9 ±0.35	7.8 ±0.9
	$\rho\pi$	5.8 ±0.3	4.1 ±0.4
	$f^0\pi^0$	0.24±0.07	
$\pi^+\pi^-MM$		35.8 ±0.8	34.5 ±1.2
	$\eta\pi^+\pi^-$	0.8 ±0.1	
$2\pi^+2\pi^-$		6.9 ±0.6	5.8 ±0.3
	$A_2^\pm\pi^\mp$ $\rightarrow \rho^0\pi^\pm$	2.0 ±0.3	
	$\rho^0 f^0$	0.90±0.2	
	$\rho^0\pi^+\pi^-$	1.50±0.3	
	$\rho^0\rho^0$	0.12±0.12	0.4 ±0.3
$2\pi^+2\pi^-\pi^0$		19.6 ±0.7	18.7 ±0.9
	$\omega\pi^+\pi^-$	3.0 ±0.3	3.3 ±0.4
	$\omega\rho^0$	2.1 ±0.2	0.7 ±0.3
	ωf^0	1.7 ±0.2	
	$\rho^0\pi^+\pi^-\pi^0$	13.7 ±0.6	7.3 ±1.7
	$\rho^\pm\pi^\mp\pi^+\pi^-$		6.4 ±1.8
	$B^\pm\pi^\mp$ $\rightarrow \omega\pi^\pm$	0.7 ±0.1	
	$\eta\pi^+\pi^-$	0.35±0.04	0.34±[illegible]
	$A_2^\pm\pi^\mp$ $\rightarrow \eta\pi^\pm$	0.13±0.0[illegible]	
$2\pi^+2\pi^-MM$		20.8 ±0.7	21.3 ±1.1
	$\eta'\pi^+\pi^-$	0.11±0.02	
$3\pi^+3\pi^-$		2.1 ±0.2	1.9 ±0.2
$3\pi^+3\pi^-\pi^0$		1.9 ±0.2	1.6 ±0.3
	$\omega 2\pi^+2\pi^-$	1.3 ±0.3	
	$\eta 2\pi^+2\pi^-$	0.17±0.07	
	$\eta'\pi^+\pi^-$	0.04±0.01	
$3\pi^+3\pi^-MM$			0.3 ±0.1

*This table updates the one published by R. Armenteros and B. French in High Energy Physics, Vol. 4 (Academic Press, Inc.), New York, 1969, with data published later by the CERN-Collège de France Collaboration. In quoting percentages for resonance production, no corrections have been made for decay modes not occurring in the given final state.

the pions for $\bar{p}p$ annihilations at rest according to a summary by Enstrom et al.[16] are: $<\pi^{\pm,o}> = 5.02$, $<\pi^{\pm}> = 3.06$, $<\pi^{-}> = 1.53$, and $<T_{\pi}> = 234$ MeV. The average number of charged pions according to Table 4 is 2.95.

It is important to note in Table 4 that there are very few $\pi^+\pi^-$ back to back events, only 0.35%. This makes it plausible to trigger on a minimum of three particles. To do this effectively, the trigger should be sensitive to the gammas from π^o. In the case of $\bar{p}p$ ($\bar{n}n$) annihilations, 3.6% have only π^o's. In 7.4% of the cases one π^o accompanies the $\pi^+\pi^-$ pair, and in 35% of the cases the number of π^o's accompanying the $\pi^+\pi^-$ pair is more than one. In all the remaining cases, the number of charged pions is 4 or more, with and without π^o accompaniment. In the case of $\bar{n}p$ annihilation, there will always be at least one π^+ and the situation is more favorable. There are also processes involving K meson emission, but we do not list them here because all of these together have a branching ratio of only 4%.

In practice the $\bar{n}$ annihilation will take place on a nuclear target. For this reason it is useful to consider the results obtained from a study of 750 MeV antineutron annihilations in a heavy liquid bubble chamber.[17] Although the chamber contained 22% by weight of Br, this accounted for only 10% of the annihilations. Most of the annihilations took place in the light elements, 18% in H, 58% in C, and 14% in F. Each annihilation gave, on average, 2.8 $\pi^{\pm}$, 1.2 π^{-} and 2.1 p. The mean kinetic energy of the pions was $\bar{E}_{\pi} = 322$ MeV, but as is shown in Figure 3 the distribution peaks below 100 MeV. An appreciable amount of energy (and momentum) goes to protons. The average energy is $\bar{E}_p = 88$ MeV. Most of the protons would be missed in all of the detectors proposed so far. These indications underline the importance of using the lightest possible element for the target.

6. The n - $\bar{n}$ Experiments

One n - $\bar{n}$ experiment has already been completed. It was carried out at the Grenoble reactor[18] and a report was given to this Workshop last year. The experiment used one of the cold neutron beams that are available at Grenoble. The conditions of the experiment were very clean. The cold neutrons, with average velocity 150 m/s are bent around a curved path by total reflection. They reach the detector virtually free of capture gammas and fast neutrons. The flux,

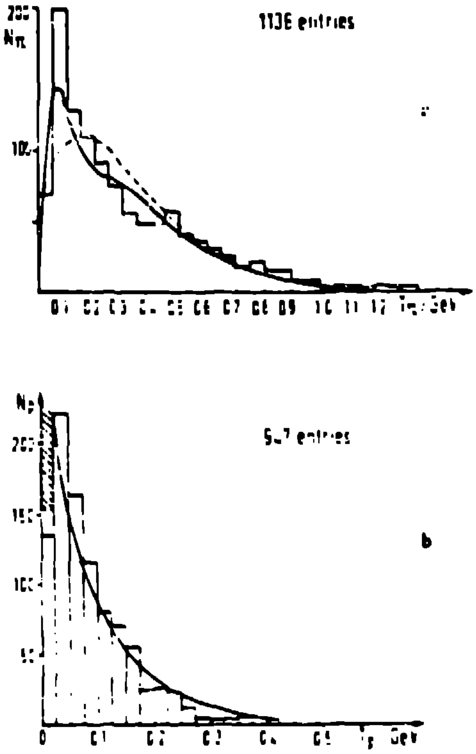

Figure 3 Kinetic energy distributions a) for pions and b) protons obtained using 750 MeV $\bar{n}$ in a heavy liquid bubble chamber. The events of the $\bar{n}p$ type which were mainly on hydrogen were excluded from the pion plot. Solid lines: results from a model; dashed line in pion spectrum: distribution for annihilations on free nucleons.

however, is low, 10^9 neutrons/s so the sensitivity of the experiment is limited to a mixing time of about 10^6 seconds. The detector was a calorimeter, a hodoscope made of alternate layers of lead and scintillator. Although an extensive anticoincidence shield against cosmic rays was provided, all the events recorded were presumed to be due to cosmic rays, as runs with and without the magnetic field and with the reactor off showed. The event rate, about 100 per day, could not be distinguished from background and limited the determination of the mixing time to $\tau > 1.2 \times 10^5$ s with a 95% confidence level. With "zero" background, this result could have been obtained in less than one day, and a limit of 3×10^6 s could be set in 100 days.

A new run is currently under way with a greatly improved arrangement. The calorimeter is now an array of limited streamer planes, sandwiched between aluminum plates. The limited streamer chambers have good spatial resolution and allow reconstruction of the events to check that they originate from the target. The limited streamer chambers cover the region behind as well as in front of the target. Altogether, 90% of the solid angle for events originating at the target is covered. There are no results available at this time, but the report is that the discrimination against the background has been greatly improved.

A second experiment is currently being mounted in Pavia.[19] The neutron source is a Triga reactor. Although this reactor is only 250 kw, it is being adapted exclusively for this experiment. The full area of the thermal column is being utilized, together with a long flight path and a large target area. As a result, a sensitivity $\tau \doteq 10^7$ s is anticipated even though the neutrons will be at room temperature and not cooled.

The other experiments[20] are all at the proposal stage. They attempt to exploit neutron sources of higher intensity to extend the sensitivity beyond 10^7 s, possibly even somewhat above 10^8 s. These proposals require either substantial modification of the neutron source and/or a more elaborate detector. Thus, these experiments, if they come off at all, are some years down the road. In considering their relative merit, it is important to judge whether the detector has sufficient power in fact to discriminate against background events well enough to achieve the "zero" background condition that is assumed in quoting sensitivity.

7. Detector Problems

The detector will not operate properly in the presence of the large fluxes of fast neutrons and capture gamma rays that normally accompany the production of thermal neutrons. The Grenoble solution, cold neutrons and a curved beam path is the most elegant but the loss of neutron intensity is a major limitation. The Grenoble experimenters hope that a more intense beam of this type will be built and that by increasing the length of the flight path as well as the area of the target they will be in a position to exceed 10^8 seconds in sensitivity. The other proposals do not contemplate the use of neutrons colder than room temperature at this stage. In the experiments using a nuclear reactor the neutrons are extracted over a large area close to the core and care must be taken in the design of the moderator to reduce the fast neutron and gamma ray fluxes that come from the core. This is done by a suitable arrangement of bismuth slabs within the moderator, although it is hard to do this without some loss in thermal neutron intensity. It helps to place the detector as far away from the reactor as possible, i.e., a long drift distance. It also helps to use a thin target through which most of the neutrons and gamma rays in the beam can pass without interacting until they reach a beam stop far beyond. The target, of course, must be thick enough to stop any of the antineutrons which may have appeared in the beam. This leads to a detector in the form of a cylinder which surrounds the target and subtends as large a solid angle around it as practical. Openings have to be left for the beam to enter and leave, to end up in the beam stop beyond. A series of baffles in the drift tube upstream of the detector is used to collimate the beam, to make it strike the target but not the inside wall of the detector around it.

In the proposal using an accelerator as a neutron source, advantage is taken of the pulsed beam. The time of flight of gamma rays and fast neutrons down the drift tube is very different from the slow thermal neutrons and allows gating the detector to respond only to the slow neutrons.

8. Cosmic Ray Background

The problem of the cosmic ray background is more subtle. We want to be sure that the one event we may see after 200 days of running is not due to one of the 10^{11} cosmic rays that have passed through the detector in that time. Even with an effective anti-coincidence shield to protect the detector against charged particles in the cosmic rays, the uncharged particles, neutrons and wide angle bremsstrahlung, remain in sufficient number to cause plenty of mischief.

9. Detector Criteria

The successful detector must distinguish annihilation from cosmic ray events unambiguously, but it's hard to know how elaborate (and expensive) a detector has to be to meet this requirement. It does this best if it measures as many as possible of the quantities that characterize an annihilation event, namely:

1) Spatial reconstruction that identifies a vertex at the target.
2) Temporal reconstruction that shows the particles to be moving from the vertex, not toward it.
3) Identification of each particle, showing that by charge, energy, and momentum, it is a likely component of an annihilation channel.

4) The multiplicity is that of a probable annihilation channel.

5) The total energy is consistent with 2 GeV.

6) The total momentum is consistent with zero.

All detectors have limited space, time, energy, and momentum resolution. In particular, since the annihilation takes place in a nuclear target, not all the energy can be made visible, and some of the momentum will be taken up by nuclear recoil and remain unseen. Better results can be obtained at greater cost by elaborating the detector. The problem is to know what is good enough. In this the proposals differ.

We have already seen how, in the first Grenoble experiment, calorimetry plus crude spatial resolution was not enough. It remains to be seen how the new arrangement which incorporates greatly improved spatial resolution for reconstructing the vertex will work out. The other experiments deal with the problem in different ways.

10. Summary of n - $\bar{n}$ Experiments

Table 5 summarizes the neutron sources used or contemplated in the experiments. Table 6 summarizes the detector characteristics. Table 7 summarizes the main parameters of each experiment, giving the "zero" background sensitivity for a 200 day run at 90% confidence level.

11. Omega West Experiment

As an example of a proposed experiment whose description has not been given before, I give an overview of the layout and design of the Los Alamos Omega West experiment. Figure 4 shows the general layout. The Omega West reactor lies at the bottom of a narrow canyon. The 50 meter drift tube extends across the canyon, with the detector building cut into the canyon wall. A useful amount of cosmic ray shielding is provided thereby. Figure 5 shows some detail at the reactor. Inside the reactor building the drift tube is 24 inches in diameter and shielded with iron plates to keep the radiation levels down in the vicinity of the reactor. Figure 6 shows how the detector building is set in the rock of the canyon wall. It also shows the layout of the detector and the beam stop. Figure 7 shows how the detector is set inside its building. The overburden on the roof of the building provides shielding against the neutrons in the cosmic rays coming from

Table 5 Neutron Sources

Grenoble:	57-MW Reactor: cold neutrons 25°K curved beam guide 20 cm x 3 cm low γ, low fast n $\phi = 10^9$ n/s $\bar{v} = 160$ m/s $\lambda = 20$ Å
Pavia:	0.25 MW Reactor: thermal neutrons Area 1.2 m x 1.2 m Bi+Paraffin moderator $\phi = 2 \times 10^{11}$ n/s at target
Oak Ridge:	30 MW Reactor: thermal neutrons Area 1400 cm^2 $\phi = 5 \times 10^{13}$ n/s at 1 m^2 target at 20 m $\phi = 7 \times 10^{12}$ n/s at target with Bi+D$_2$O moderator
Los Alamos LAMPF:	Proton Linac 580 μA Heavy Metal Beam Stop, D$_2$O moderator $\phi = 2$-4×10^{12} n/s thermal neutrons (1 m target at 30 m)
Los Alamos Omega West:	8 MW Reactor: thermal neutrons Channel tangent to core $\phi = 3 \times 10^{11}$ n/s (1.5 m target at [illegible])
Chalk River:	110 MW Reactor: thermal neutrons channel tangent to core $\phi = 1 \times 10^{12}$ n/s (1.5 m target at [illegible])
Grenoble III:	Guide area 100 cm^2, $\lambda = 10$ Å $\phi = 1 \times 10^{12}$ n/s (1 m target at [illegible])

above. Figure 8 is a longitudinal section of the detector. A cross-sectional view of the detector near its central region is shown in Figure 9. The arrangement of the counters at the ends is shown in Figure 10. The baffling along the drift tube is shown in Figure 11. The detector surrounds a 6 foot (2 meter) diameter thin beryllium target inside the drift tube. The drift tube at this location is a 6 foot diameter evacuated aluminum tube fitted with a magnetic shield. The detector is made entirely of liquid scintillation counters copied from the design of K. Lande, et al.[21] in their Homestake Mine

Table 6 Detectors

Grenoble I:	Pb scintillator calorimeter 760 kg 10% active. Acceptance 25% of 4π Thick target ^{6}LiF
Grenoble II:	Limited streamer tubes + Al plates Tracking calorimeter. Acceptance 95% of 4π Thick target ^{6}LiF
Pavia:	Pb-flash chamber tracking calorimeter 65% of 4π acceptance Scintillator hodoscope + resistive plate chambers for trigger Thin target C or Be
Oak Ridge:	Pb-glass Čerenkov counter + scintillation counter hodoscope 90% of 4π acceptance
LAMPF:	Time of flight and tracking chambers Temporal + spatial reconstruction 93% of 4π acceptance No calorimetry
Los Alamos Omega West:	Time of flight + calorimetry: using liquid scintillator 95% of 4π acceptance Checks momentum balance

proposal to study proton decay. The liquid scintillator is held in polyvinylchloride (PVC) containers 26 feet long, 1 foot by 1 foot in cross section. The scintillators close to the drift tube are 6 inches by 6 inches in cross section. The scintillators are viewed at each end by 5 inch hemispherical photomultipliers. These scintillators have an attenuation length of 8 meters and a time resolution (measured) of 3 ns FWHM. A 4 foot gap separates the inner ring of scintillators from the innermost of the outer rings of scintillators. Thus, by time of flight measurements it becomes possible to tell whether particles are moving from inside out or from outside in. The full array of scintillators is used for calorimetry. The scintillators make visible 84% of the energy deposited. A large fraction of the charged pions are stopped within

Table 7 $n \to \bar{n}$ Experiment

$\nu = (t/\tau)^2 \Phi T \epsilon$

$t = \ell/v \quad T = 1.73 \times 10^7$ s (200 d) $\quad \tau = 10^7$ s

Experiment	drift length ℓ m	drift time $t=\ell/v$ s	neutron flux Φ ns^{-1}	Figure of Merit Φt^2 ns	detection efficiency ϵ	no. events for $T=10^9$ s ν	sensitivity at "zero" background τ_{min} 90% CL s
Grenoble II	6	3×10^{-3}	10^9	9×10^3	0.35	0.054	1.5×10^6
Pavia	16	7×10^{-3}	3×10^{11}	1.4×10^7	0.50	1.3	0.7×10^6
Oak Ridge	20	8×10^{-3}	4×10^{13}	3×10^9	0.50	215.	1×10^8
(with Bi-D_2O moderator)			6×10^{12}	4×10^8	0.50	29.	4×10^7
LAMPF							
(probable)	30	1.4×10^{-2}	2×10^{12}	4×10^8	0.50	34.	4×10^7
(possible)			4×10^{12}	8×10^8	0.50	68.	5×10^7
Omega West	50	2.3×10^{-2}	3×10^{11}	1.5×10^8	0.50	13.	2×10^7
Grenoble III	35	9×10^{-2}	10^{12}	8×10^9	0.50	700.	1.7×10^8

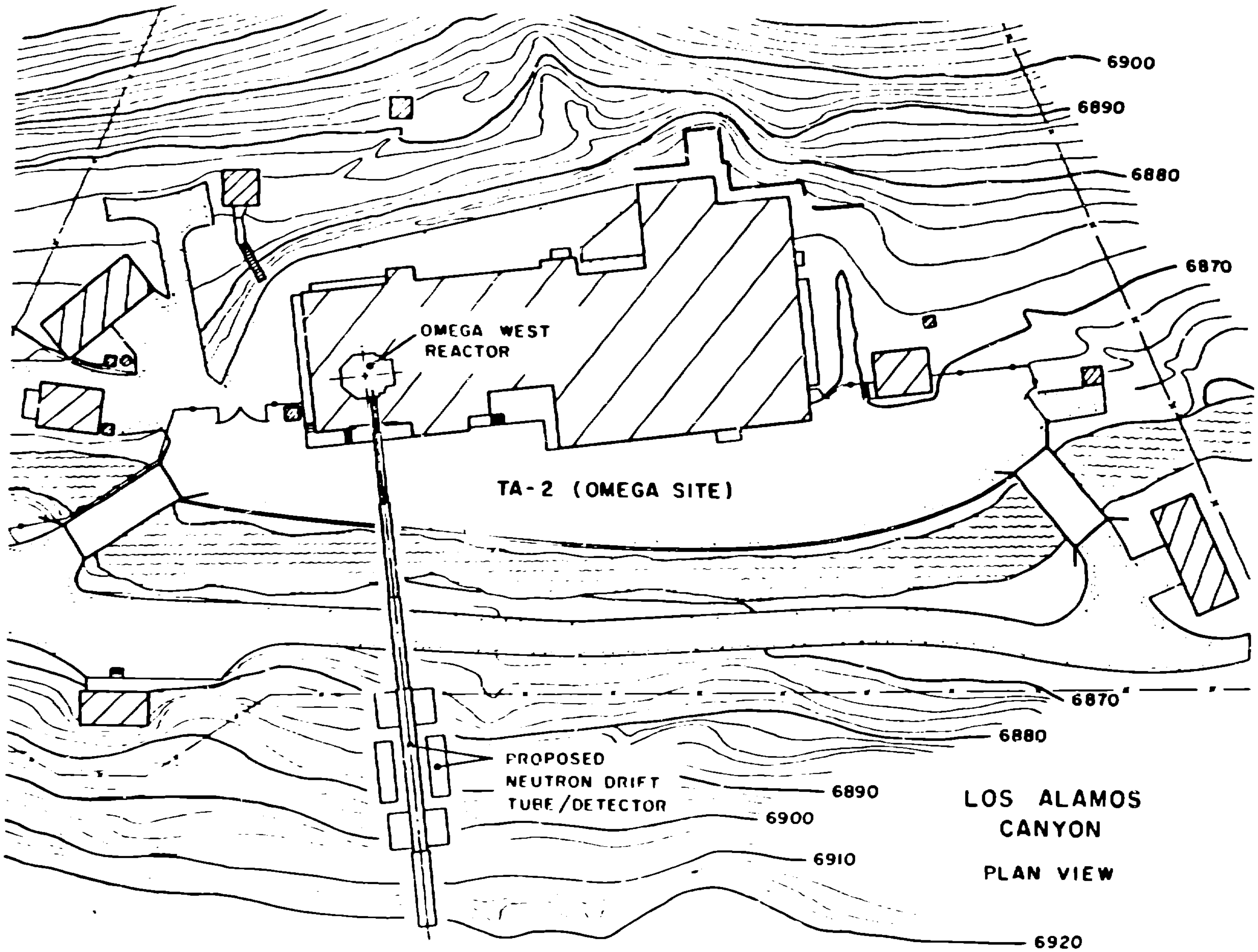

Figure 4 General layout of Omega West reactor n - n̄ conversion experiment.

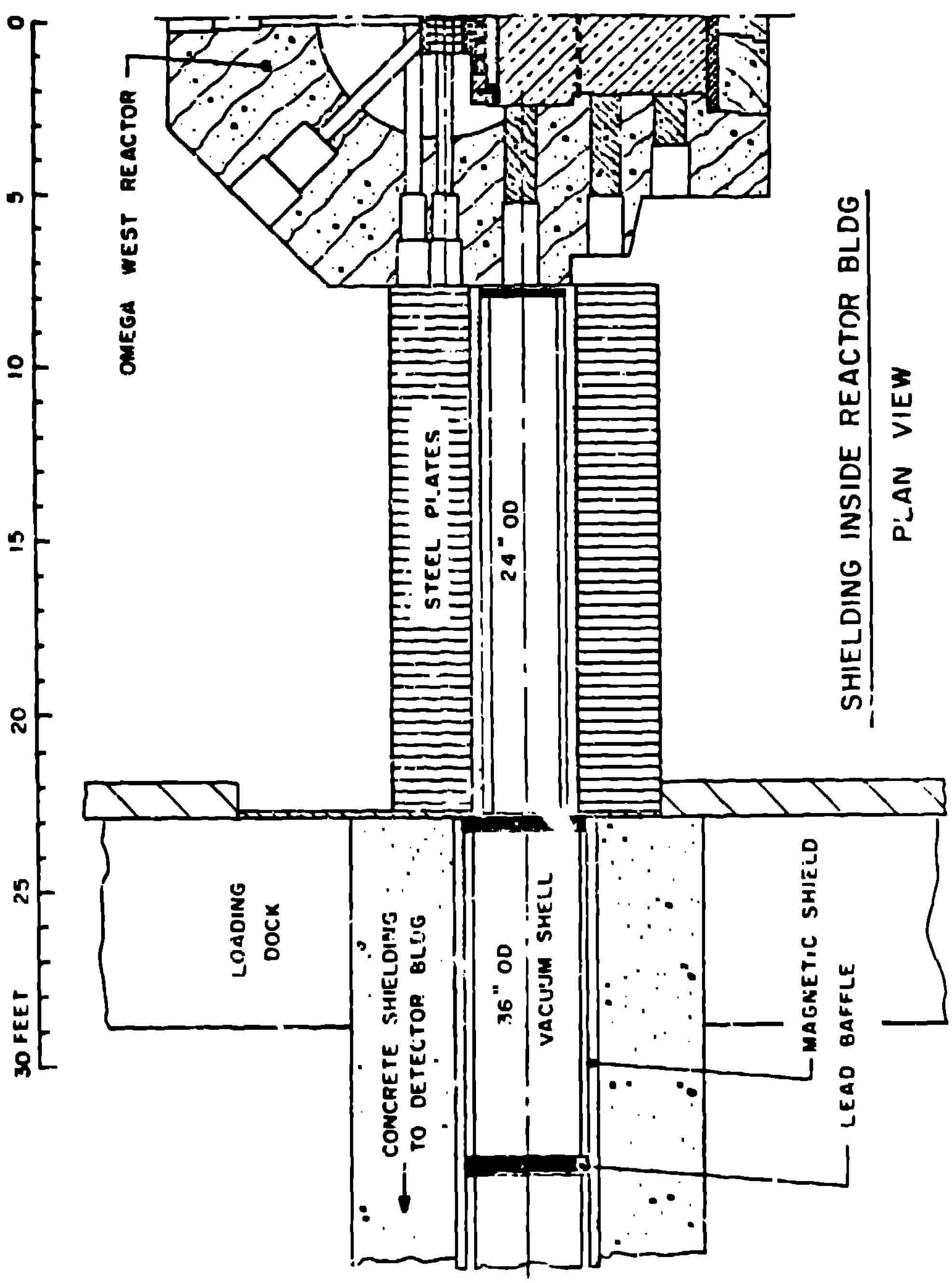

Figure 5 Detail at the reactor. Iron shielding keeps radiation level down inside the reactor building.

the detector by nuclear interaction. Since the nuclear disintegration energy is recorded by liquid scintillator, the rest mass of the pion is included in the energy measurement. Moreover, since the direction of the particle is measured by time of flight it is possible to determine the momentum from the energy measurement of each of the particles that fall within the acceptance, which is 95%. The calorimeter is made thick enough to contain a large fraction of the electromagnetic energy

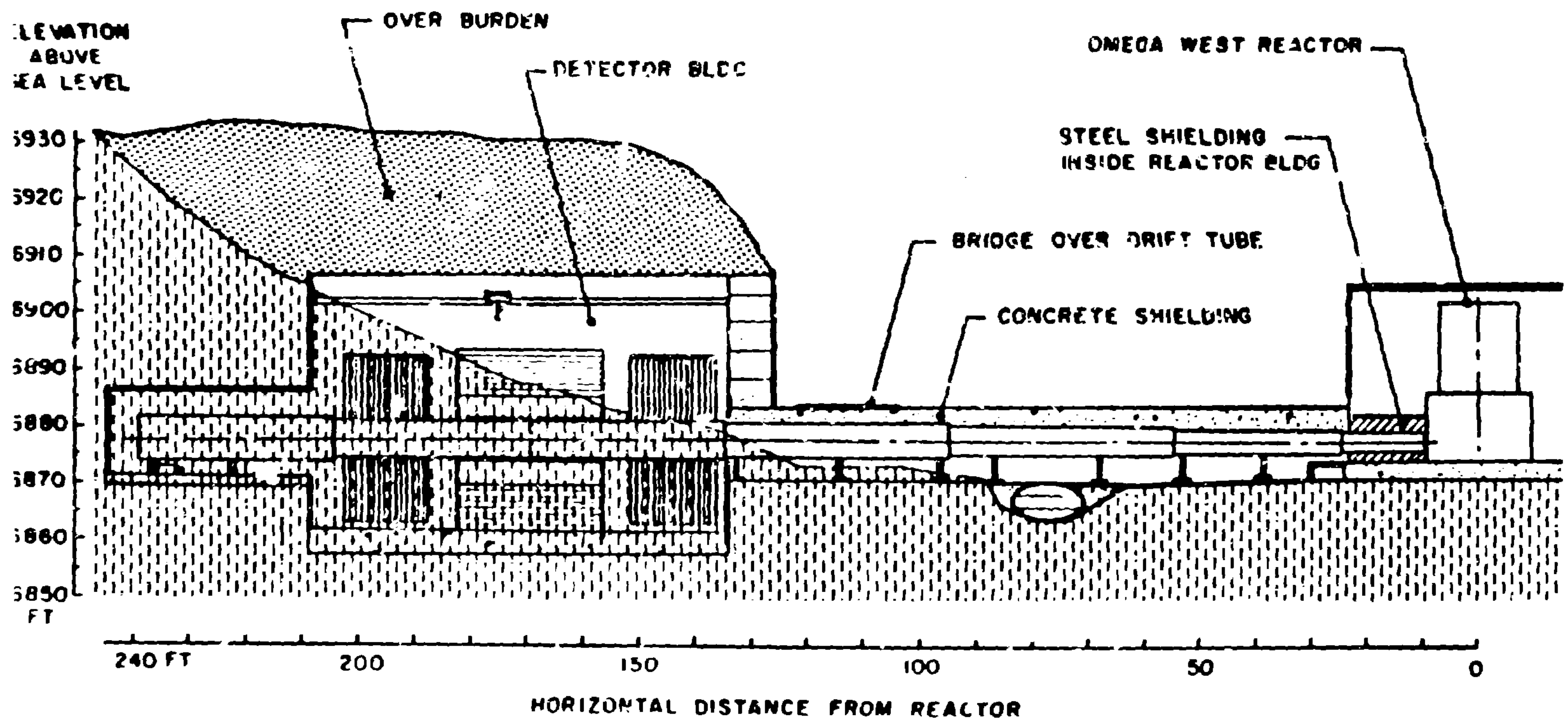

Figure 6 Detector building set in canyon wall.

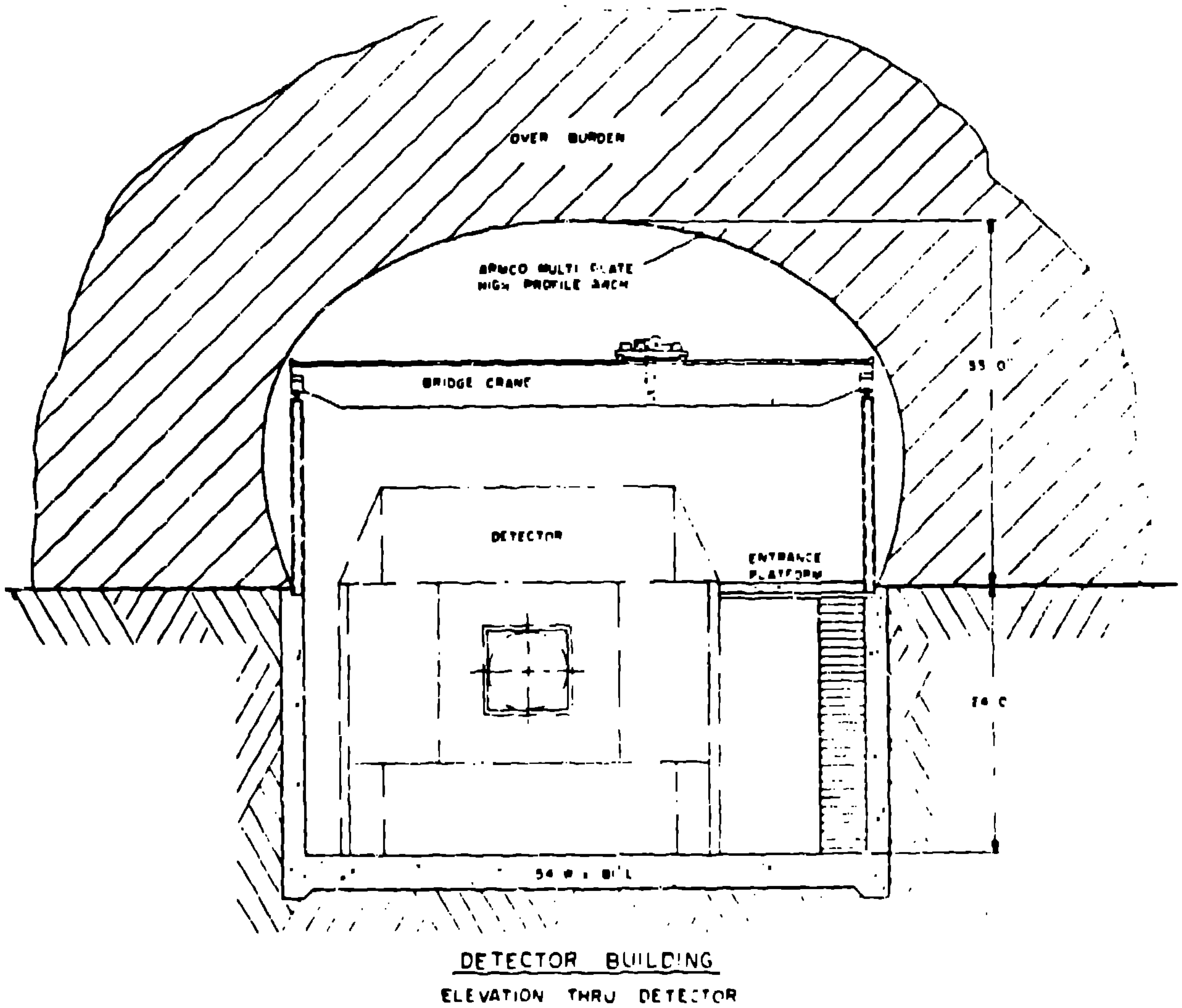

Figure 7 Detector building, cross-sectional view with the detector in place.

from the π^0's. The scintillators are thick enough to provide a useful means for discriminating against capture gamma rays. The energy deposited by ionization in 15 cm of scintillator is about 27 MeV, much higher than the maximum possible, 7 MeV, from the capture gamma rays. With a capture gamma ray flux $<10^8\ s^{-1}$ entering the detector, pile-up is not a serious problem and a simple discriminator at each phototube will make the detector rather insensitive to the capture gamma rays. The time of flight capability is used to veto cosmic ray events.

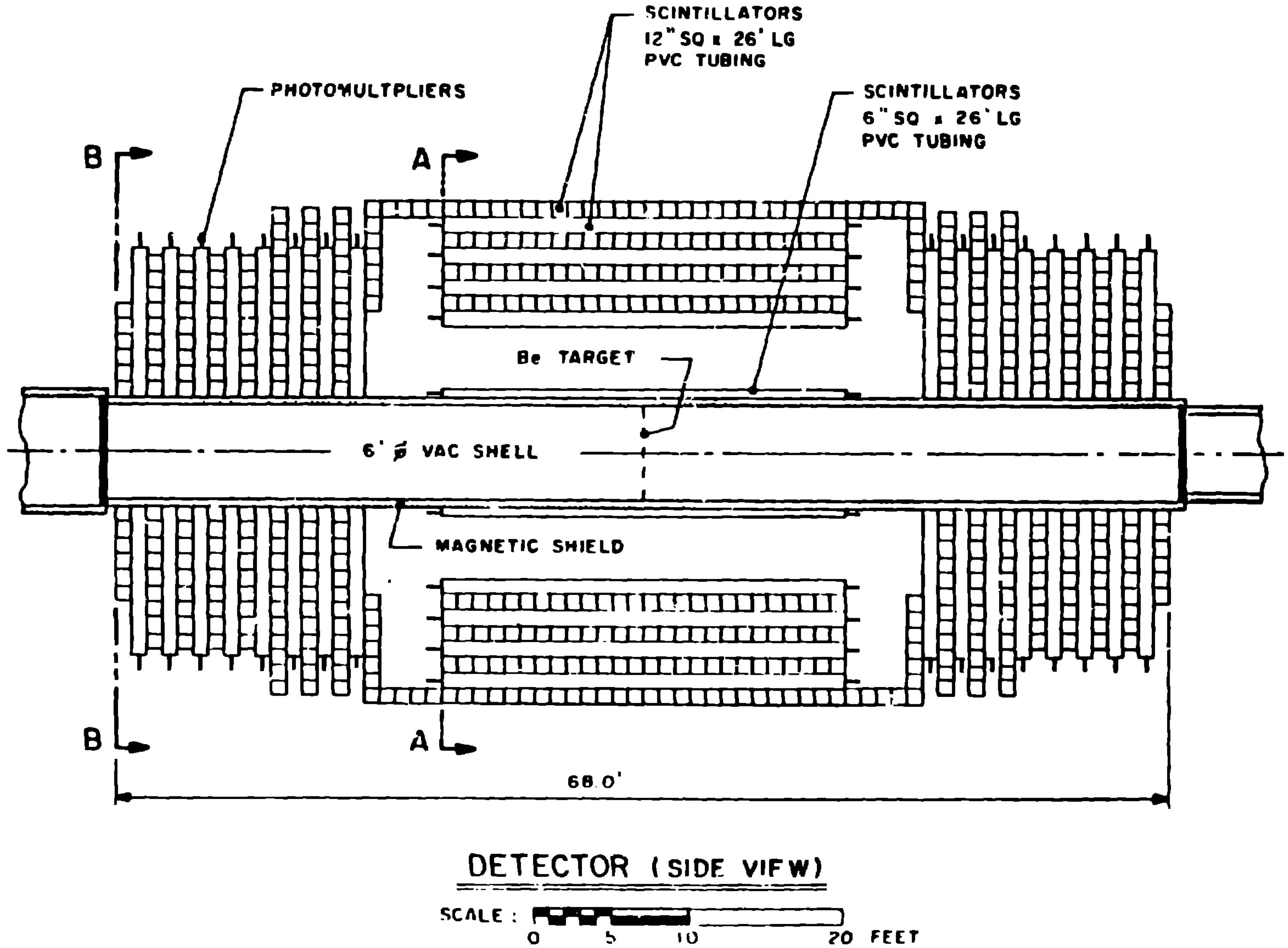

Figure 8 Detector: Longitudinal view showing disposition of 26' x 1' x 1' scintillator modules.

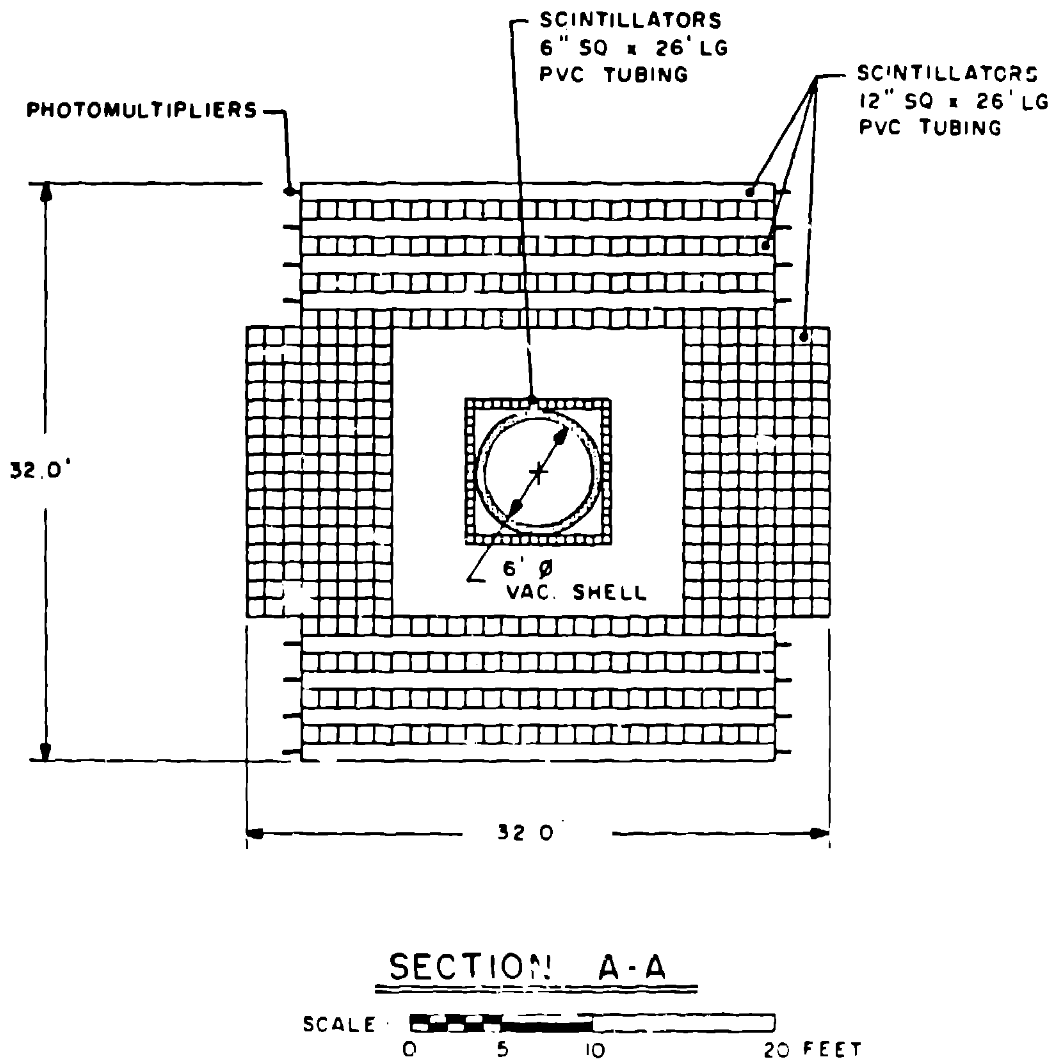

Figure 9 Cross-sectional view of detector in central region.

A veto is provided whenever the time of flight measurement clearly shows that there is a particle moving toward the inside of the detector. The spatial resolution of this detector, without the use of chamber planes, is about 30 cm. This should be sufficient to demonstrate by spatial and temporal reconstruction that the event originates near the target and that energy and momentum balance as well as multiplicity corresponds to what is probable from an annihilation event.

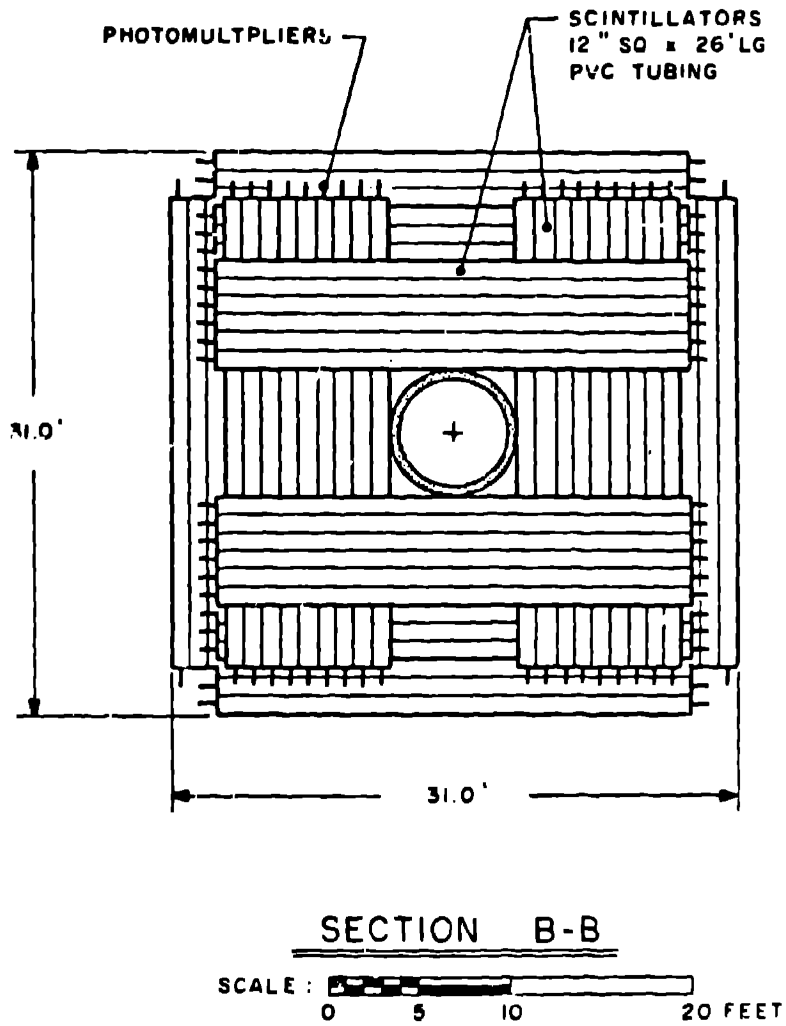

Figure 10 Cross-sectional view of end counters.

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*Talk presented at the Third Workshop on Grand Unification, The University of North Carolina, Chapel Hill, NC, April 11-17, 1982.

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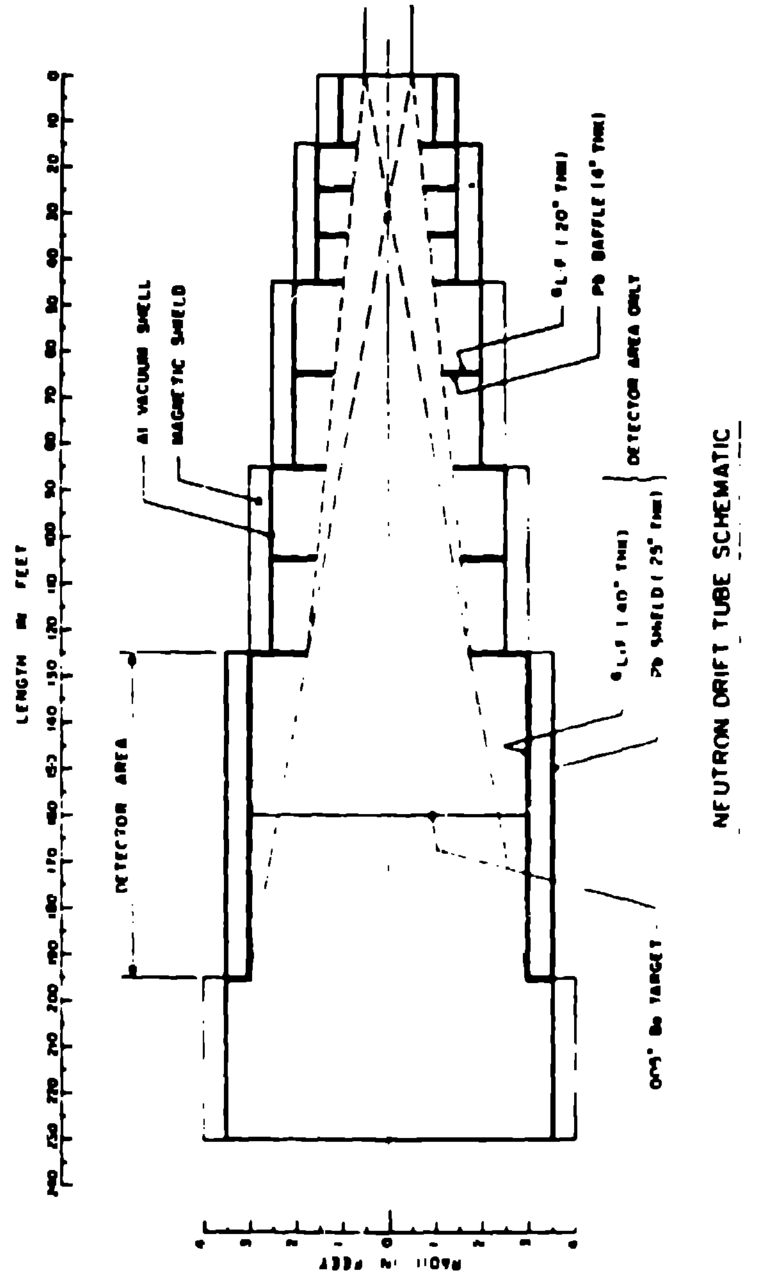

Figure 11 Baffling along the drift tube.

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